# ESTCP
# Cost and Performance Report

(WP-0304)

## Development of Ferrium® S53 High-Strength, Corrosion-Resistant Steel

January 2009

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

# Report Documentation Page

*Form Approved*
*OMB No. 0704-0188*



| | | |
|---|---|---|
| 1. REPORT DATE<br>**JAN 2009** | 2. REPORT TYPE | 3. DATES COVERED<br>**00-00-2009 to 00-00-2009** |

| | |
|---|---|
| 4. TITLE AND SUBTITLE<br>**Development of Ferrium S53 High-Strength, Corrosion-Resistant Steel** | 5a. CONTRACT NUMBER |
| | 5b. GRANT NUMBER |
| | 5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | 5d. PROJECT NUMBER |
| | 5e. TASK NUMBER |
| | 5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>**Environmental Security Technology Certification Program (ESTCP),4800 Mark Center Drive, Suite 17D08,Alexandria,VA,22350-3605** | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | 10. SPONSOR/MONITOR'S ACRONYM(S) |
| | 11. SPONSOR/MONITOR'S REPORT NUMBER(S) |

12. DISTRIBUTION/AVAILABILITY STATEMENT
**Approved for public release; distribution unlimited**

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT<br>**unclassified** | b. ABSTRACT<br>**unclassified** | c. THIS PAGE<br>**unclassified** | **Same as Report (SAR)** | **47** | |

**Standard Form 298 (Rev. 8-98)**
Prescribed by ANSI Std Z39-18

# COST & PERFORMANCE REPORT
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## ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| AFB | Air Force Base |
| AFMC | Air Force Materiel Command |
| AIM | Accelerated Insertion of Materials |
| ALGLE | Aging Landing Gear Life Extension |
| AMS | Aerospace Materials Specification |
| ASTM | American Society for Testing and Materials |
| | |
| C-MAT | Calculation for Material Alternative Technologies |
| Cd | Cadmium |
| CRES | corrosion resistant |
| CVN | Charpy V-notch |
| | |
| El | Elongation |
| ESOH | environmental, safety, and occupational health |
| ESTCP | Environmental Security Technology Certification Program |
| | |
| Fcy | compressive yield stress |
| FOD | foreign object damage |
| FPI | fluorescent penetrant inspection |
| Fsu | shear strength |
| Ftu | tensile ultimate strength |
| Fty | tensile yield strength |
| | |
| HVOF | high-velocity oxygen-fuel |
| | |
| JTP | Joint Test Protocol |
| | |
| $K_{IC}$ | fracture strength |
| $K_{ISCC}$ | stress corrosion fracture strength |
| | |
| MIL-HDBK-5 | Mil Handbook 5 |
| MIL-STD | Military Standard |
| MLG | main landing gear |
| MMPDS | Metallic Materials Property Development and Standardization (handbook) (formerly MIL-HDBK-5) |
| MPI | magnetic particle inspection |
| MRO | maintenance, repair, and overhaul |
| | |
| NDI | non-destructive inspection |
| NPV | net present value |
| | |
| OEM | original equipment manufacturer |
| OO-ALC | Ogden Air Logistics Center |

## ACRONYMS AND ABBREVIATIONS (continued)

| | |
|---|---|
| OSHA | Occupational Safety and Health Administration |
| PEL | permissible exposure limit |
| PPE | personal protective equipment |
| RA | reduction in area |
| REACH | Registration, Authorization and Restriction of Chemicals (European regulation) |
| RoHS | Restriction of Hazardous Substances (European regulation) |
| SCC | stress corrosion cracking |
| SERDP | Strategic Environmental Research and Development Program |
| SPO | System Program Office |
| TRL | Technology Readiness Level |
| USAF | U.S. Air Force |
| UTS | ultimate tensile strength |
| VAR | Vacuum Arc Remelting |
| YS | yield strength |

# ACKNOWLEDGEMENTS

The financial and programmatic support of the Environmental Security Technology Certification Program (ESTCP), under the direction of Dr. Jeffrey Marqusee, Director, and Mr. Charles Pellerin, Program Manager for Pollution Prevention, is gratefully acknowledged. In addition, the financial and programmatic support of the Aging Landing Gear Life Extension Program (ALGLE) is also gratefully acknowledged.

The authors would also like to express thanks to the following individuals who made substantial contributions to the execution of the project:

- Paul Trester, General Atomics
- David Tibbitts, General Atomics
- Charles Kuehman, QuesTek Innovations
- Brian Tufts, QuesTek Innovations
- Keith Legg, Rowan Technology Group
- Doug Wiser and Craig Edwards, ES3, who initiated the program at Hill Air Force Base (AFB).



Principal Investigator: Ryan Josephson
Hill AFB

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# 1.0 EXECUTIVE SUMMARY

## 1.1 BACKGROUND

S53 was developed under Strategic Environmental Research and Development Program (SERDP) funding as an alternative to the use of Cadmium (Cd)-plated high-strength landing gear steel. QuesTek Innovations LLC had developed the Materials by Design methodology in which alloys could be designed from first principles using a computational approach that avoided the need for the extensive trial-and-error formulation and testing that has been the mainstay of the alloy manufacturing industry since its inception. S53 was designed to be equivalent in mechanical properties to Cd-plated 300M ultrahigh strength steel used in landing gear, and equivalent in corrosion resistance to the lower strength 15-5PH stainless steel used in actuators. It also replaces 4340 and 4340M steels and other high-strength steels (such as 4330 and HP9-4-30) used in landing gear and actuators. There is also a potential for using S53 in place of lower strength corrosion-resistant (CRES) steels such as 15-5PH, 17-4PH, and PH13-8Mo, which are used in applications such as hydraulic actuators that require a combination of strength and corrosion resistance.

## 1.2 OBJECTIVES OF THE DEMONSTRATION

The demonstration objectives were twofold:

1. To demonstrate and validate the Materials by Design methodology for developing new alloys.
2. To demonstrate and validate a CRES steel that would be mechanically equivalent to 300M ultrahigh strength landing gear steel, but with corrosion resistance equivalent to 15-5PH stainless steel used in modern aerospace actuators.

These objectives were met, with two minor exceptions: (1) the tensile yield of S53 is slightly lower than 300M (213 ksi min versus 230 ksi min), although ultimate (to which landing gear are designed) was the same (280 ksi) and (2) under corrosion testing, S53 visually corrodes more rapidly than the target 15-5PH, although the pit growth rate is only a little higher (and it is pit depth that drives condemnation). Only service experience will show whether the difference is significant.

## 1.3 REGULATORY DRIVERS

The regulatory drivers are Cd and its concomitant $Cr^{6+}$ conversion, both of which have become more severe over the past few years. Cd is a heavy metal poison, a known carcinogen[1] and a teratogen[2]. It tends to accumulate in soil and lakes, causing damage to marine life and plants and entering the food chain. It has many serious health effects. The Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) for Cd is 5µgm $m^{-3}$ per 8-hour shift, while the PEL for $Cr^{6+}$ was also recently lowered to 5µgm $m^{-3}$. In addition, both Cd and $Cr^{6+}$ are highly restricted under the European Restriction of Hazardous Substances (RoHS) rules

[1] DHHS National Toxicology Program, 10th Report on Carcinogens (Dec 2002).
[2] Teratogen is an agent that causes birth defects through fetal damage.

(although they currently exempt aerospace uses) and are likely to be ultimately banned under the European Registration, Authorization and Restriction of Chemicals (REACH) statute. (REACH already bans Cd plate on vehicles but still permits it for the time being on aircraft.) By eliminating Cd and $Cr^{6+}$, S53 removes all the environmental and health issues associated with these materials.

## 1.4 DEMONSTRATION RESULTS

The demonstration showed that a new alloy could be accurately designed and optimized in a far shorter time by the computational method, while ensuring that both the thermodynamics and kinetics were correct. Other CRES steels designed in the traditional Edisonian manner have met the mechanical requirements but were not producible or scalable because the properties could only be obtained in small batches.

All the properties and performance relevant to qualifying for landing gear were measured. The alloy meets all the requirements but is more resistant to corrosion and corrosion-related failures such as stress corrosion cracking (SCC) and hydrogen embrittlement. In addition, it is more damage-tolerant because of its somewhat higher fracture toughness and is more resistant to grind burns and arc burns that can occur in depot maintenance. In addition, removal of Cd eliminates the Cd embrittlement that can occur when brakes and gear are overheated, which can occur on aborted takeoff. The mechanical properties are summarized below:

| | Fty[1] (ksi) | Ftu[2] (ksi) | El[3] (%) | RA[4] (%) | Fcy[5] (ksi) | Fsu[6] (ksi) | Hardness (Rc) | CVN[7] (ft-lb) | $K_{IC}$[8] (ksi$\sqrt{\text{in}}$) |
|---|---|---|---|---|---|---|---|---|---|
| 300M min | 230 | 280 | 8 | 30 | 247 | 162 | | | 40-60 avg |
| S53 min | 213 | 280 | 8 | 30 | 247 | 162 | | | 50 |
| S53 average | 225 | 288 | 14-16 | 55-65 | 255 | 181 | 54 | 18 | 66 |

[1]Fty = tensile yield strength
[2]Ftu = tensile ultimate strength
[3]El = Elongation
[4]RA = reduction in area
[5]Fcy = compressive yield stress
[6]Fsu = shear strength
[7]CVN = Charpy V-notch
[8]$K_{IC}$ = fracture strength

The axial, notch, and bending fatigue properties of S53 are better than or equal to 300M, while the corrosion fatigue is significantly better. S53 can be plated and high-velocity oxygen-fuel (HVOF) sprayed, although some plating does require the use of a Ni strike. The standard depot non-destructive inspection (NDI) methods such fluorescent penetrant inspection (FPI), magnetic particle inspection (MPI), and Barkhausen work as well on S53 as on 300M. The only method that does not work is Nital etching for grind burns because the CRES steel cannot be etched in the same way. The alternative Barkhausen (Roll Scan) method works, however.

The major difference between S53 and 300M is cost, with 300M being about \$3-5/lb and S53 being about \$15-20/lb (about the same cost as the Aermet 100 used on most Navy gear). This does not mean, however, that S53 components are five times as expensive since most of the cost is in the fabrication. The cost premium for components examined varied from 40% to 80%. It was found that S53 was most cost-effective for components that are relatively complex (raw materials a smaller proportion of the cost, and are frequently condemned for corrosion-related causes, or lead to corrosion-related service failures. C-5 roll pins and B-1 main landing gear (MLG) cylinders were particularly cost-effective to replace. For components that have serious service failure issues, replacement will be a judgment of risk rather than cost.

## 1.5 STAKEHOLDER/END-USER ISSUES

A new alloy cannot be used unless it has a commercial producer, aerospace specifications, and engineering allowables. S53 has, or will shortly have, all of these—two licensed manufacturers (Cartech and Latrobe), an Aerospace Materials Specification (AMS), AMS 5922, a Metallic Materials Property Development and Standardization (MMPDS) listing of Class A allowables, and an International Alloy Number (UNS S10500).

The Air Force is carrying out a full-scale rig test of an A-10 landing gear fabricated from S53. This is a critical test required before A-10 gear can be flight tested. Because S53 has not been used previously on any other landing gear components, it must successfully pass the A-10 System Program Office (SPO) required tests and checks to ensure that it is flight worthy. Given that the existing gear is fabricated from 4330, a lower strength steel, S53 is a very low risk replacement.

A 12-month flight test is planned for one of the S53 A-10 cylinders manufactured during this program. The aircraft will proceed through its standard daily operations, and the S53 piston will go through periodic inspections for damage and corrosion throughout the 12-month evaluation period. A successful evaluation will show that the S53 piston can perform without any problems or failures in its designed manner in a typical environment.

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# 2.0 TECHNOLOGY DESCRIPTION

## 2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

**Technology background and theory of operation:** S53 was developed as an alternative to the use of Cd-plated high-strength landing gear steel. QuesTek Innovations LLC had developed the Materials by Design methodology in which alloys could be designed from first principles using a computational approach that avoided the need for the extensive trial-and-error formulation and testing that has been the mainstay of the alloy manufacturing industry since its inception. The aim of the program was twofold:

1. To demonstrate and validate the Materials by Design methodology for developing new alloys
2. To demonstrate and validate a CRES steel that would be mechanically equivalent to 300M ultrahigh strength landing gear steel but with corrosion resistance equivalent to 15-5PH stainless steel used in modern aerospace actuators.

The work was initially funded as a 1-year SERDP proof-of-principle project. In this first project an alloy was designed and an initial heat of the material was made and tested for its basic mechanical properties (yield, modulus, and ultimate). The results showed that the alloy was very close to the design propertie─a result that would have taken years by the old Edisonian methods.

A SERDP program was funded to develop the alloy fully, including its chemistry and heat treat specifications. The resulting alloy, designated S53 (for Stainless HRC 53), was fully defined, together with its heat treat and material properties.

This alloy was demonstrated and validated under Environmental Security Technology Certification Program (ESTCP) funding, while at the same time validating its implementation through the Accelerated Insertion of Materials (AIM) methodology. The dem/val work reported here evaluated all the properties and performance required for qualification as a landing gear alternative, as well as the properties required for an AMS and a MMPDS listing.

**Applicability:** Ultrahigh strength steels are used throughout the aerospace industry. Although this alloy was developed specifically for landing gear, the same properties and performance are required for a very large number of components, including hydraulic actuators and rotary gear actuators, as many smaller items such as hinges and brackets are used throughout the aircraft. In all these items, the critical requirements are yield and ultimate tensile strength (UTS), together with corrosion resistance. By eliminating the need for Cd plate, a CRES alloy avoids the many complications and limitations that come with Cd plating, including:

- Loss of corrosion protection when the surface is damaged in any way
- Accelerated corrosion fatigue and environmental embrittlement
- Hydrogen embrittlement during depot rework
- Exposure of manufacturing workers, depot personnel, and operational personnel to Cd and $Cr^{6+}$ throughout the life of the aircraft

- Elimination of Cd and $Cr^{6+}$ contamination of groundwater from wash downs
- Elimination of the need for brush Cd plating at the operational level
- Elimination of Cd and $Cr^{6+}$ from the waste streams at depots.

**Material to be replaced:** S53 replaces Cd-plated 300M ultrahigh strength steel used in landing gear. It also replaces 4340 and 4340M steels and some other high-strength steels (such as 4330 and HP9-4-30) used in landing gear and actuators. There is also a potential for using S53 in place of lower strength CRES steels such as 15-5PH, 17-4PH, and PH13-8Mo, which are used in such applications as hydraulic actuators that require a combination of strength and corrosion resistance.

**Theory of operation:** The Materials by Design methodology uses a combination of thermodynamic and kinetic modeling with alloy data to develop the alloy from first principles. The basic approach is shown in Figure 1. The desired performance is obtained by designing the chemistry and processing steps to obtain the correct microstructure, which in turn produces the materials properties that the performance requires.

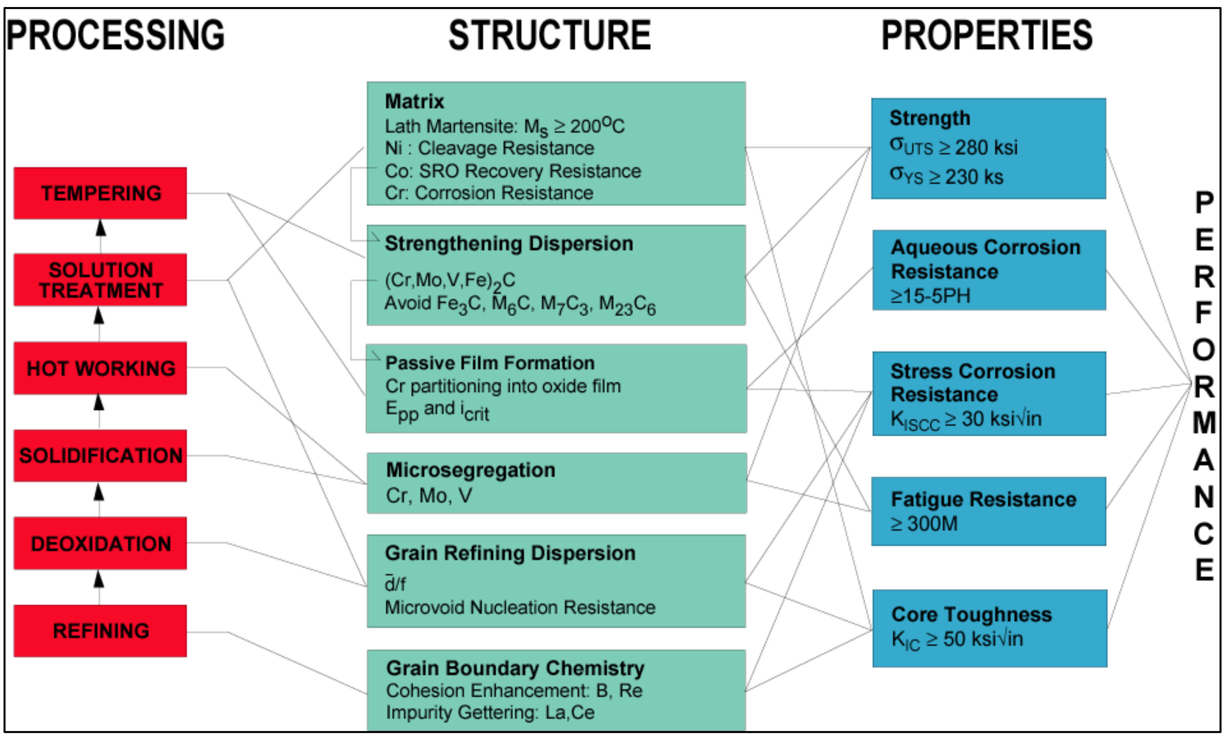


**Figure 1. Principles of Materials by Design Methodology.**

## 2.2 PROCESS DESCRIPTION

**Operational requirements:** S53 is an alloy that is essentially no different to use than 300M or other landing gear alloys. It is a material that will be primarily worked at the original equipment manufacturer (OEM) level. There are a number of operations, all of which have been evaluated in this program:

- Forging
- Machining
- Grinding
- Heat treating
- Shot peening
- Coating and plating
- Non-destructive inspection (NDI)
- Passivating
- Priming and finishing

While the details of these processes are a little different (for example feeds and speeds for grinding and machining and the details of the heat treating process), there is no fundamental difference between using S53, 300M, or any other high-strength steel. No special tools or grinding wheels are required. The only significant differences with S53 are

- Machining and grinding tests show that these operations are a little slower with S53, although with experience they are likely to become very similar.
- The heat treatment is more complex and includes several cryogenic steps that are not widely available at heat treaters. Thus heat treating for mechanical properties is not something that would be done in-house at most fabricators (which is also true for other high-strength steels). However, simple heat treats used in depots such as hydrogen baking or stress annealing are no different.
- S53 is passivated by an acid dip rather than Cd plated prior to sealing, priming, and painting
- Because S53 is a CRES alloy, the standard Nital etch (temper etch) cannot be used to detect grind burns.

Apart from Nital etching, all other NDI methods are the same as for other steels (FPI, MPI, Barkhausen Noise Roll Scan).

**Performance:** The performance of S53 was designed to be equivalent to the mechanical performance of 300M and to the corrosion performance of 15-5PH stainless steel. In most respects S53 exceeds the mechanical performance requirements and is similar to, or a little lower in corrosion resistance, than 15-5PH in corrosion tests. Corrosion performance can never be properly gauged from laboratory or even beach exposure testing but only from service experience.

**Specifications:** The following specifications and standards apply to S53:

1. AMS5922
2. An MMPDS listing, which is in the final stages of completion.

The alloy chemistry is shown in Table 1.

**Table 1. S53 Chemistry (Balance Fe).**

| Element | Min | Max |
|---|---|---|
| Carbon | 0.19 | 0.23 |
| Manganese | -- | 0.10 |
| Silicon | -- | 0.10 |
| Phosphorus | -- | 0.008 |
| Sulfur | -- | 0.005 |
| Chromium | 9.50 | 10.50 |
| Nickel | 5.20 | 5.80 |
| Cobalt | 13.50 | 14.50 |
| Molybdenum | 1.80 | 2.20 |
| Tungsten | 0.80 | 1.20 |
| Titanium | -- | 0.015 |
| Aluminum | -- | 0.010 |
| Vanadium | 0.25 | 0.35 |
| Oxygen | -- | 0.0020 (20 ppm) |
| Nitrogen | -- | 0.0015 (15 ppm) |

**Training:** No special training is required for using S53. However, the specifications for plating and finishing will be somewhat different than those for non-CRES high-strength steels.

**Health and Safety:** There is no difference in the basic environmental, safety, and occupational health (ESOH) requirements for using, machining, or finishing S53, except that it contains approximately 14% Co and 10% Cr, whereas 300M and similar steels contain very low levels of alloying elements. Grinding operations in the manufacturing shop and the overhaul depot are usually done under a coolant flood that controls metal dust. No additional personal protective equipment (PPE) is needed beyond that required for machining any other stainless steel. A dust mask should be worn when scuff sanding S53 for paint touch-up at the operational level to prevent the dust inhalation. Since Cd and $Cr^{6+}$ treatments are not used on S53, the level of PPE is lower than is required for scuff sanding chromated, Cd-plated steel components.

**Ease of use:** There is no significant difference in ease of use of S53 in manufacturing. At the operational level, however, operations such as wash downs, scuff sanding, and touch-up are significantly easier as neither personnel nor the environment need to be protected against Cd or chromate discharges. Neither is it necessary to brush Cd plate S53 for corrosion control. The only area where ease of use is harder is in welding, where S53, like any other stainless steel, can produce $Cr^{6+}$ fumes. However, landing gear and other high-strength steel components are never arc welded since welding is generally incompatible with the usage of these alloys in applications that demand the highest possible strength. The only welding method currently used on landing gear is friction welding, which does not create $Cr^{6+}$ fumes.

## 2.3 PREVIOUS TESTING OF THE TECHNOLOGY

The technology has been developed in two prior programs:

- SERDP proof-of-principle project—PP1149
- SERDP Project—WP-1224 "Corrosion Resistant Steels for Structural Applications in Aircraft"

Prior to the current program S53 has not been tested in any other application.

## 2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The advantages and disadvantages of S53 compared with 300M are summarized in Table 2.

**Table 2. Advantages and Disadvantages of S53 versus 300M.**

| Advantages/Strengths | Disadvantages/Limitations |
|---|---|
| **Technical:** | |
| Better corrosion and mechanical performance | Lower yield (Fty*) |
| Much better resistance to SCC failure (higher $K_{ISCC}$**) | More complex heat treatment |
| More resistant to hydrogen embrittlement and re-embrittlement | Cannot be Nital etched for grind burn detection |
| More resistant to grind burning | |
| Eliminates risk of Cd embrittlement on aborted takeoffs, hard brake landings | |
| **Depot and OEM fit:** | |
| Lower probability of condemnation for embrittlement or grind burning | Only two current vendors |
| Lower corrosion pit depth (less grinding generally needed to remove corrosion) | Significantly higher material cost |
| **Environmental:** | |
| No Cd plating, brush Cd plating, or chromate conversion | |
| No Cd or chromate release on scuff sand or wash down | |

*Fty = tensile yield strength
**Stress corrosion fracture strength

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# 3.0 DEMONSTRATION DESIGN

## 3.1 PERFORMANCE OBJECTIVES

Table 3 summarizes the goals of the program.

**Table 3. Performance Objectives.**

| Property | Program Goal | 300M | S53 Typicals | S53D Best Estimate |
|---|---|---|---|---|
| UTS | >280 ksi min | 280 ksi min | 290 ksi | 290 ksi |
| YS* | >230 ksi min | 230 ksi min | 215-225 ksi | 220 ksi |
| % El | 10% min. longitudinal<br>7% min. transverse | -- | 15-17% | 15% |
| Reduction of area | 35% min. longitudinal<br>25% min. transverse | -- | 60% | 60% |
| $K_{IC}$ | 50 ksi√in min | ~60 ksi√in | 75-90 ksi√in | >75 ksi√in |
| Fatigue | Similar to 300M | -- | ~300M | ~300M |
| Cleanliness | AMS 2300, ASTM E45 | -- | √ | √ |
| SCC** | >40 ksi√in min | ~15 ksi√in | 45-60 ksi√in | 50 ksi√in |
| Corrosion resistance | ~15-5 PH ASTM E85 (USN)<br>~13-8 Mo ASTM B117 (Civil/USAF***) | N/A | √ | √ |
| Embrittlement resistance | 200 hrs @ 75% UTS post plating<br>200 hrs @ 45% UTS 5% NaCI | -- | Not tested | √ |
| Crack growth | Better than 300M | -- | √ | √ |

*YS = yield strength
**SCC = stress corrosion cracking
***USAF = U.S. Air Force

Of the quantitative performance objectives, only the yield stress was not met. Since most landing gear are designed to ultimate, not to yield, this was not considered critical. Yield stress, Fty, is arbitrarily defined as 0.2% offset from the elastic curve. S53 does not meet this value because the shape of the stress-strain curve is slightly different from 300M because the hardening mechanisms are not identical.

## 3.2 SELECTION OF TEST FACILITY AND PLATFORM

Ogden Air Logistics Center (OO-ALC) was chosen as the principal test facility since this is the Air Force landing gear overhaul and repair depot. However, due to the nature of the project major testing was carried out throughout the steel manufacturing infrastructure:

- Steel manufacture was done at Cartech in Reading, Pennsylvania.
- Forging of A-10 landing gear was carried out at Kropp Forge in Chicago, which has the die needed for this particular component since they supply A-10 forgings to the landing gear manufacturer.

- Heat treating was done at the Rex Heat Treating Co. of Lansdale, Pennsylvania.
- Machinability tests were done by the landing gear manufacturer, Heroux Devtek in Montreal.
- Laboratory data were taken at General Atomics, QuesTek, and Northwestern University.

### 3.3 TEST FACILITY HISTORY/CHARACTERISTICS

OO-ALC at Hill Air Force Base (AFB) has been in operation for over 50 years and has been managing U.S. Air Force (USAF) landing gear systems since its inception. The systems managed at Ogden are KC-135, E-3, B-2, B-52, C-5, C-141, C-130, F-16, F-15, A-10, and T-38.

All the above weapon systems use high-strength, low alloy steel for the majority of their landing gear structural components. All these components use cadmium plating for corrosion protection, and the development of S53 will have a direct impact on these weapon systems.

The chief landing gear engineer at OO-ALC (Sandra Fitzgerald) is the cognizant authority for landing gear overhaul technology changes for Air Force sustainment.

All current design high-strength steel landing gear require cadmium plating, which, together with other plating processes, is a source of hydrogen embrittlement failure on those occasions when the hydrogen bake is not performed correctly (e.g., oven failure). Corrosion is the primary reason for condemnation of Air Force landing gear components (see Figure 2), usually because corrosion pits cannot be removed. Doing so reduces the wall thickness below the allowable limit. For overhaul the Cd must typically be stripped and replated in the Hill AFB plating shops.

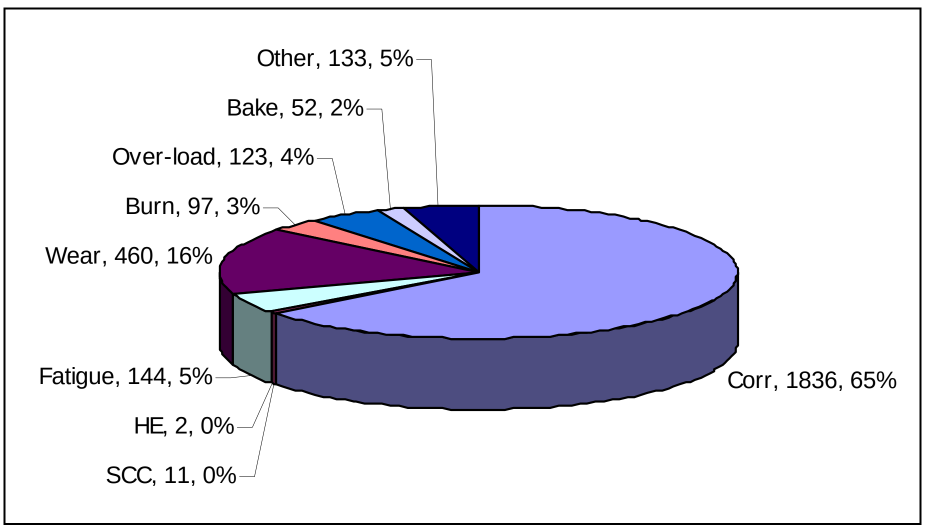



**Figure 2. Causes of Condemnation—Form 202.**

Eliminating the need for Cd plating eliminates Cd plating at Ogden, chromate conversion of all Cd-plated components, and brush Cd plating for corrosion control and touch-up at the operational level. S53 is not, however, a route to eliminating Cd plating at the depot, since most landing gear will not be replaced with S53 because of the prohibitive cost of replacing the legacy

gear. Rather it is a means to eliminating Cd plate on problem components that are frequently condemned for corrosion-related causes, or that experience a high level of service failures.

## 3.4 PHYSICAL SETUP AND OPERATION

Changes to the material from which landing gear are made requires no changes to facilities. The test program ran from 2003 through 2007. Tests are continuing under other USAF funding, including rig testing of A-10 landing gear.

## 3.5 SAMPLING/MONITORING PROCEDURES

The test program involved measurements of all the producibility, properties, and performance parameters required to validate and qualify S53 as well as to develop AMS specifications and MMPDS Class A allowables. The following testing was carried out, with test specifications shown in brackets (where appropriate):

- ❑ Heat Treating Effects
  - Solution treatment
  - Continuous cooling transformation
  - Cryogenic treatment
  - Tempering response
- ❑ Producibility
  - Production of large-scale ingots of Ferrium S53
  - Fabrication of billet and bar
  - Product uniformity measurements based on hardness
  - Machinability
  - Grinding and abusive grinding
  - Plating/coating investigation (Cr, Al, Ni, Cd, high velocity oxygen fuel [HVOF])
  - NDI inspection (FMPI and Barkhausen)
  - Painting/finishing
  - Development of prime and paint specifications
  - Forging
    - Hand forgings
    - Die forging
    - Machining evaluation of forged material
- ❑ Mechanical Properties
  - Tensile properties (American Society for Testing and Materials [ASTM] E8)
  - Compressive strength (ASTM E9)
  - Bearing strength (ASTM E238)
  - Fsu (NASM 1312-20)
  - Fracture toughness (K1C), ASTM E399-90
  - SCC (ASTM F519)
  - Fatigue
    - High-cycle axial fatigue of S53 and 300M (ASTM E466)
    - Axial fatigue of electroplated specimens of S53 and 300M (ASTM E466)
    - Notched fatigue (ASTM E466)

- Corrosion fatigue
  - Charpy impact testing (ASTM E23)
  - Fatigue crack growth rate (ASTM E647)
- ❑ Corrosion Properties
  - Neutral salt fog (ASTM B117)
  - Outdoor exposure testing
  - SCC vulnerability
  - Cyclic polarization testing (ASTM G5)
  - Hydrogen embrittlement (ASTM F519)
- ❑ Qualification rig testing—A-10 MLG Piston

The material for this program was produced as a series of full-scale industrial heats of steel (10,000 and 3,000 lb). The heat treating effects testing involved a series of thermal tests to determine the best heat treating conditions, which were then used for all specimens tested under this program.

Producibility testing involved the testing of the primary operations that the landing gear undergoes in manufacture service and overhaul in order to ensure that it would meet the requirements. There are no standard tests for these requirements.

The mechanical and corrosion tests followed standard ASTM procedures wherever those were available and relevant. However, ASTM tests were supplemented with additional tests where necessary. Outdoor exposure was carried out both at a beach test site and an inland light industrial site.

Qualification rig testing was not carried out under the Joint Test Protocol (JTP), but is being done under USAF funding.

## 3.6 ANALYTICAL METHODS

The materials testing requirements and acceptance criteria for all the above tests were delineated in the JTP, which followed the test specifications. Sufficient data points were taken in all cases to ensure the statistical validity of the results.

In particular, specimens were excised from bar stock and a die-forged A-10 piston in specific locations and orientations as defined in ASTM E399-90 in order to evaluate mechanical properties in both the longitudinal and transverse directions (along and across the bar). A total of 10 industrial heats were tested from different suppliers to create sufficient data to determine MMPDS Class A allowables, which are required for design.

# 4.0 PERFORMANCE ASSESSMENT

## 4.1 PERFORMANCE DATA

### 4.1.1 Optimized Heat Treat

The following was defined as the optimized heat treatment for full strength:

1. 1985°F +/- 27 (1085°C +/-15) 60 minutes + 10, -0
2. Oil quenching or equivalent
3. Cool to -100°F (-73°C) or lower for 1 hour +2,-0 (within 8 hours of quenching)
4. 934°F +/-12 (501°C +/-7) 3 hours +/-0.5
5. Oil quenching or equivalent
6. Cool to -100°F (-73°C) or lower for 1 hour +2,-0 (within 8 hours of quenching)
7. 900°F +/-18 (482°C +/-10) 12 hours +2,-1 and air cooling.

### 4.1.2 Product Uniformity

The properties of S53 were found to be uniform and isotropic across any bar or forging, while the properties were reliable from batch to batch, even between different steel producers. This means that complex shapes will have the same properties throughout.

### 4.1.3 Machinability

Machinability testing was carried out by Heroux Devtek in Montreal, a manufacturer of many legacy replacement and new landing gear for USAF. The tests consisted of most of the milling, drilling, tapping, grinding, and other machining operations required for the manufacture of landing gear. Satisfactory feeds and speeds were developed and the machining rates relative to 300M were measured.

### 4.1.4 Plating

Plating tests were carried out with electroplates of Cd, hard chrome, Ni, and Al (AlumiPlate). It was found to be necessary to use a Ni strike to ensure good adhesion of Cd and Al, especially under fatigue. This is not unexpected since the chrome oxide layer that builds up immediately on all CRES steels on exposure to air makes them more difficult to activate and plate.

### 4.1.5 Mechanical Properties

Ferrium S53 was found to be isotropic, i.e., longitudinal and transverse values are statistically equivalent. This is important since it ensures that there will not be weak points in complex forgings, for example.

The primary mechanical properties of S53 are compared with 300M in Table 4. In most cases S53 is identical (MMPDS does not give a minimum fracture strength [$K_{IC}$] value for 300M.).

**Table 4. Primary Mechanical Properties of S53 vs 300M.**

| | Fty (ksi) | Ftu[1] (ksi) | El[2] (%) | RA[3] (%) | Fcy[4] (ksi) | Fsu[5] (ksi) | Hardness (Rc) | CVN[6] (ft-lb) | $K_{IC}$ (ksi√in) |
|---|---|---|---|---|---|---|---|---|---|
| 300M min | 230 | 280 | 8 | 30 | 247 | 162 | | | 40-60 avg |
| S53 min | 213 | 280 | 8 | 30 | 247 | 162 | | | 50 |
| S53 average | 225 | 288 | 14-16 | 55-65 | 255 | 181 | 54 | 18 | 66 |

[1]Ftu = tensile ultimate strength
[2]El = Elongation
[3]RA = reduction in area
[4]Fcy = comprehensive yield stress
[5]Fsu = shear strength
[6]CVN = Charpy V-notch

The only value for which S53 is low is Fty. The onset of early yielding in S53 is driven by transformation plasticity. The small amount of austenite remaining in the material after heat treatment converts on stress more easily than the high-strength martensite. Because this yielding is not slip, (in the traditional sense) S53 is still stable despite the small strain.

Figure 3 shows that even when Ferrium S53 exhibits lower yield strength, the overall behavior is similar to 300M. For instance, if yield was defined as 0.4% offset instead of the traditional (but arbitrary) 0.2% offset, S53 would be equivalent to 300M.

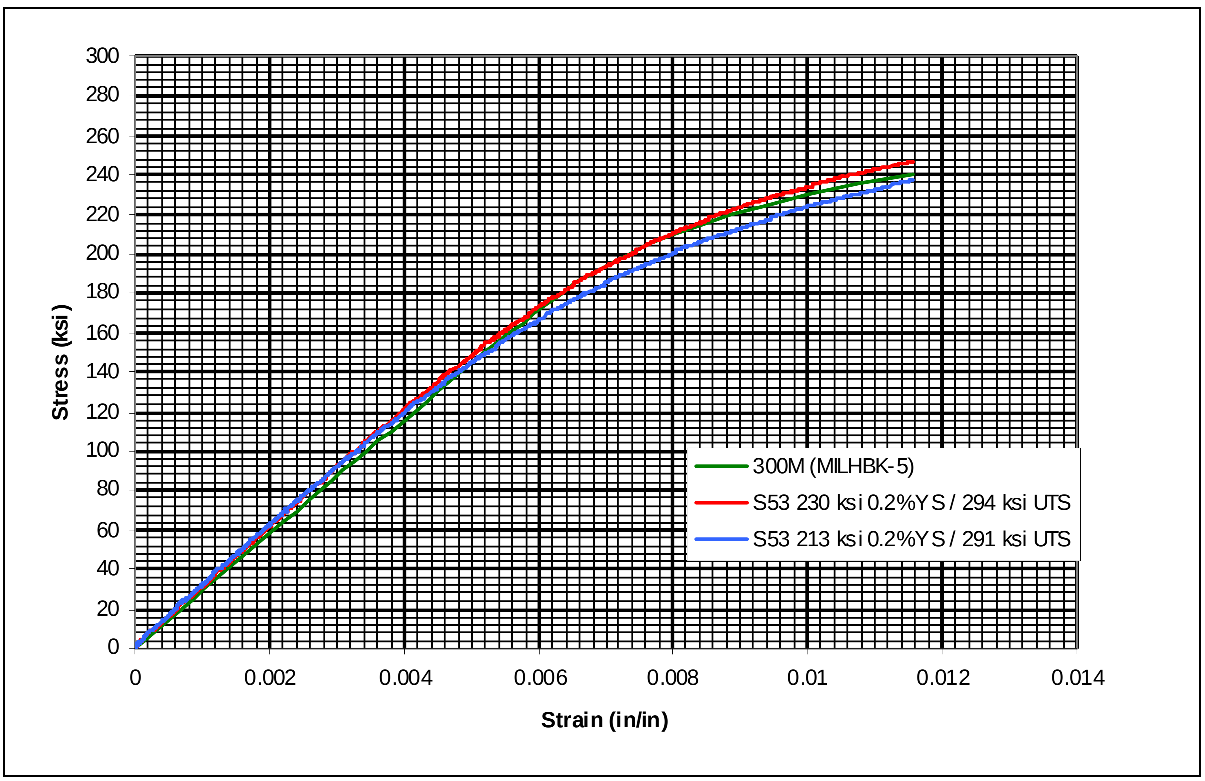



**Figure 3. Tensile Stress-Strain Curves for Two Heats of S53 versus 300M.**

### 4.1.6 Stress-Corrosion Cracking

The SCC behavior is shown in Figure 4. As the figure shows, 300M is very prone to SCC failures. S53's SCC behavior is similar to that of 15-5PH stainless steel; however, it is important to note the S53 samples tested were 90 ksi higher in strength.

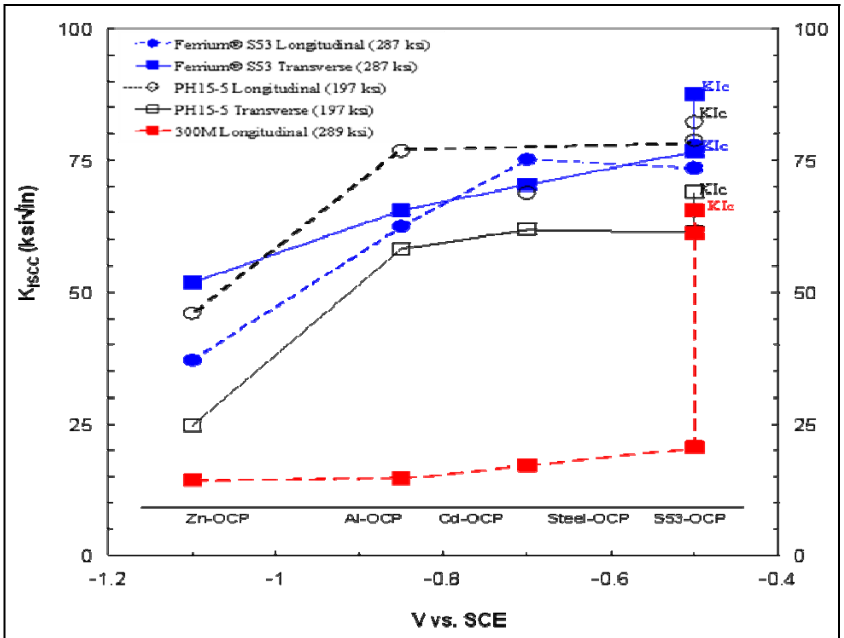



**Figure 4. $K_{ISCC}$ Comparison of Ferrium® S53, Ph15-5, and 300M Using ASTM F1624-99 Rising Step Load Test in 3.5% NaCI Solution.**

### 4.1.7 Fatigue

Fatigue measurements were done using hourglass specimens. The fatigue data for various heats and laboratories are shown in Figure 5. S53 performance was at least as good as, and in most cases, better than 300M.

The fatigue debit due to hard chrome and duplex Ni + hard chrome (used for thick rebuild) are similar for S53 and 300M. Notched fatigue performance was also measured and, again, S53 was better than 300M.

Rotating beam fatigue was run for both unpeened and shot peened S53, as shown in Figure 6. Note that the effect of shot peening on S53 is quite small. This means that if the shot peening is omitted there is little effect on component life; lack of shot peening is an occasional source of 300M component failure or recall.

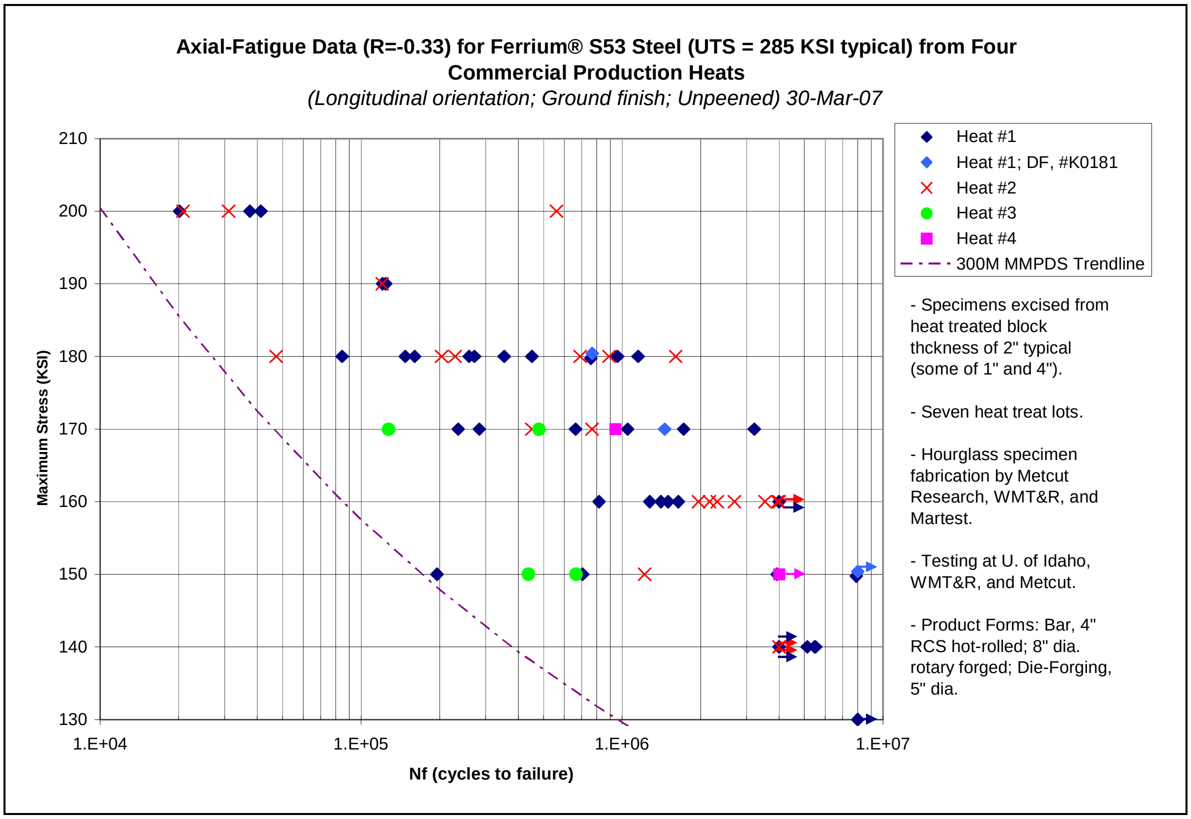



**Figure 5. Axial-Fatigue Data Conducted at an R = -0.33 to Monitor Bar from Multiple Production Heats and Product Forms of S53** (Unpeened).

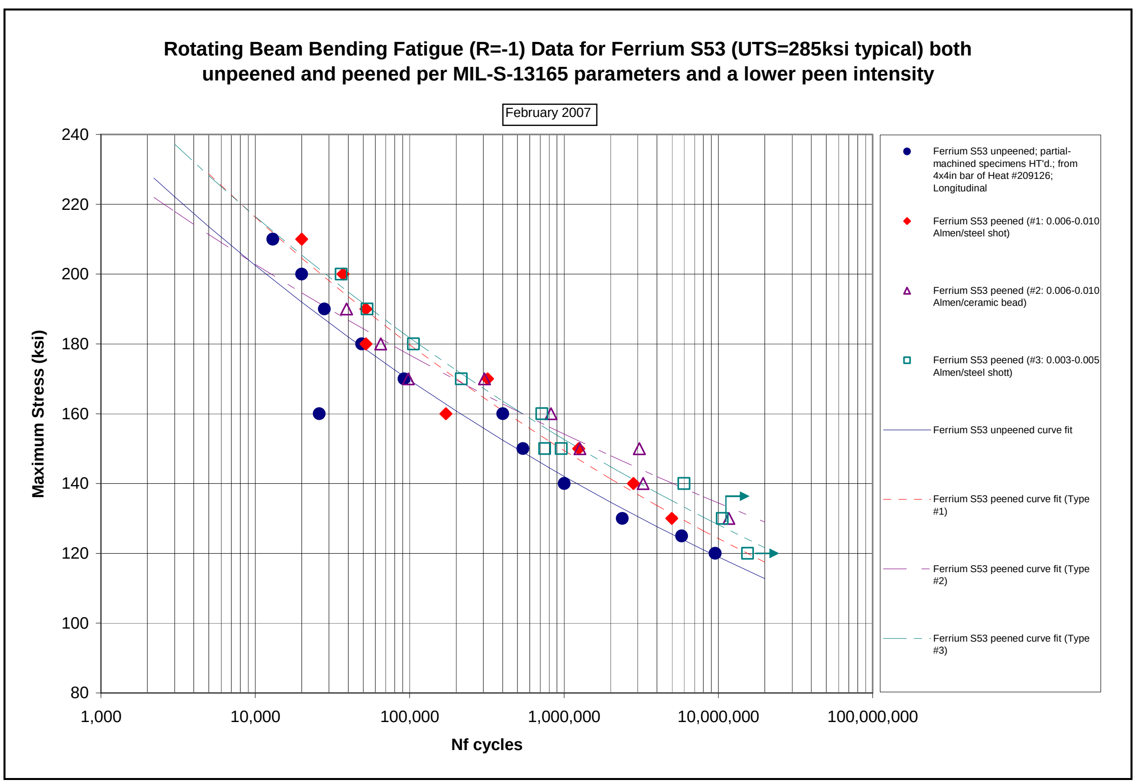



**Figure 6. Rotating Beam Fatigue of S53 with and Without Shot Peening.**

Corrosion fatigue performance is shown in Figure 7. As expected, S53 is significantly better than 300m and somewhat better than 4340, although corrosion fatigue is very much worse than fatigue in air. The S53 specimens exhibited significantly fewer SCC cracks, with a single crack growing to failure, whereas the 300M and 4340 both had multiple cracks serving as fatigue initiation sites.

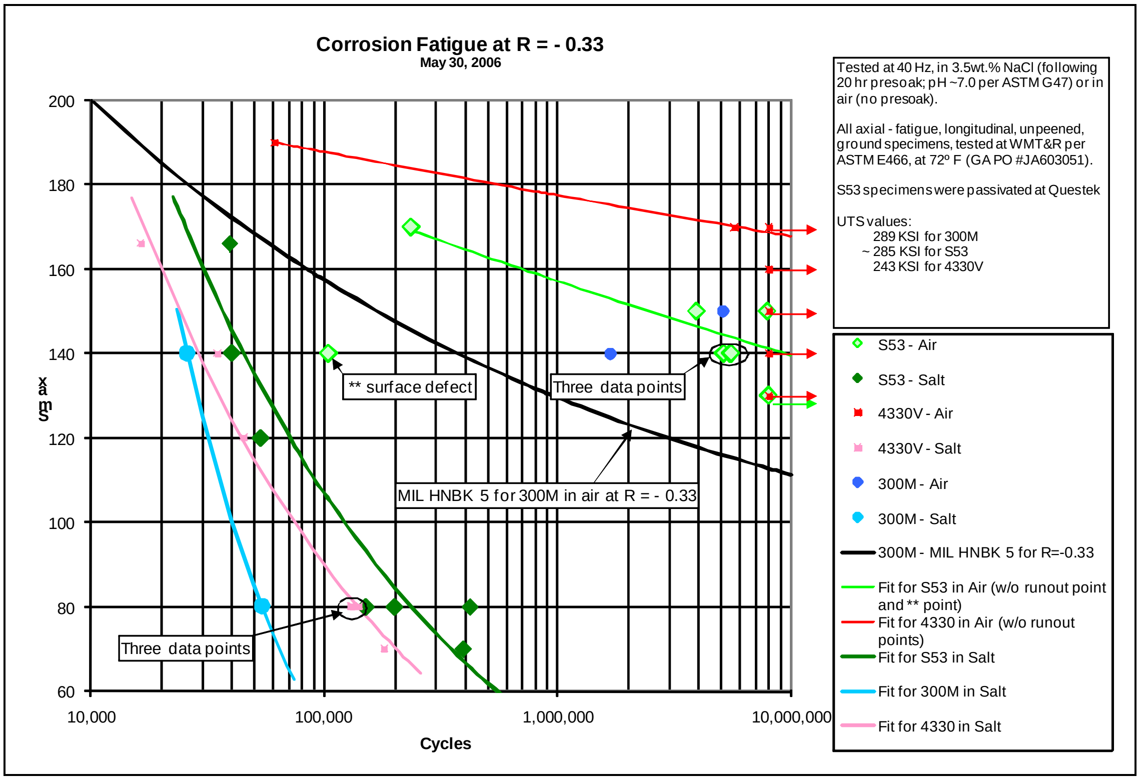



**Figure 7. Corrosion Fatigue of S53 versus 4330 and 300M.**

### 4.1.8 Corrosion

Corrosion performance was measured by ASTM B117 salt fog testing, beach exposure (Kure Beach) and rooftop exposure (Chicago). Table 5 shows the appearance rankings of the different steels with different surface treatments after a 12-month exposure at Kure Beach.

The surface of the S53 began to visually deteriorate more rapidly than PH15-5 (but far slower than 300M), and at the end of the year the S53 was completely covered with corrosion products (Figure 8). The weight gains of 300M and A100 over the year were 2 gm and 1.2 gm, respectively, versus 0.2 gm for PH15-5 and 0.3 gm for S53.

## Table 5. Appearance Ratings of Cd-Plated 300M and A100 Compared with PH15-5 and S53 (Kure Beach exposure, 1 year).

| Evaluation of Surface-Treated Test Panels (1/2 in X 3 in X 5 in) Exposed in the Oceanfront Marine Atmospheric Test Lot: LaQue (Kure Beach, NC) | | | | | |
|---|---|---|---|---|---|
| Exposure Date: 2/15/2005<br>Inspection Date: 2/21/2006<br>ASTM D-610-01 | | | Orientation: 30° facing east<br>Exposure Period: 12 months | | |
| Steel Substrate & Panel ID | Panel Corrosion* Skyward Slide | Panel Corrosion* Groundwater Slide | Observation Comments: Skyward Slide | Observation Comments: Groundwater Slide | Pre-Test Surface Treatments |
| **Aermet 100; 53 HRC** | | | | | |
| AM-1 | 7-P | 7-P | 3.8.10 | 10 | Grill Blast + Shot Peen + Cad Plate + Chromate |
| AM-2 | 6-P | 6-P | 1.10 | 1.10 | Grill Blast + Shot Peen + IVD-AJ Plate + Chromate |
| AM-3 | 9-P | 9-P | 10 | 9.10 | Grill Blast + Cad Plate + Chromate |
| AM-4 | 5-P | 6-P | 4.9.10 | 4.9.10 | Grill Blast + IVD-AJ Plate + Chromate |
| AM-5 | Removed 8/15/05 | | | | Grill Blast + Clean |
| **300M; 54 HRC** | | | | | |
| 300M-1 | 9-P | 8-P | 9.10 | 4.10 | Grill Blast + Shot Peen + Cad Plate + Chromate |
| 300M-2 | 6-P | 6-P (7-P) | 4.9.10 | 4.10 | Grill Blast + Shot Peen + IVD-AJ Plate + Chromate |
| 300M-4 | 6-P (7-P) | 5-P (5-P) | 4.5.9.10 | 4.10 | Grill Blast + IVD-AJ Plate + Chromate |
| 300M-5 | Removed 8/15/05 | | | | Grill Blast + Clean |
| 300M-7 | 7-P | 6-P | 4.9.10 | 4.10 | Grill Blast + Cad Plate + Chromate |
| **PH 15-5; 42 HRC** | | | | | |
| 15-5-1 | 9-P | 7-P | 10 | 9.10 | Shot Peen + Cad Plate + Chromate |
| 15-5-2 | 6-P | 5-P | 1.4.10 | 1.4.10 | Shot Peen + IVD-AJ Plate + Chromate |
| 15-5-3 | (4-P, 4-G) | (5-G, 5-P) | 1.5.6 | 5.6 | Shot Peen + Passivate + Chromate |
| 15-5-4 | (4-P, 4-G) | (5-G, 5-P) | 1.5.6 | 5.6 | Shot Peen + Passivate |
| 15-5-5 | Removed 8/15/05 | | | | Grill Blast + Passivate + Chromate |
| 15-5-6 | (3-P, 6-G) | (4-G, 4-P) | 1.6 | 5.6 | Grill Blast + Passivate |
| 15-5-7 | (3-P, 6-G) | (4-G, 5-P) | 1.6 | 5.6 | Grill Blast + Clean |
| **Ferrium S53A; 54 HRC** | | | | | |
| S53A-1 | 7-P | 7-P | 8.10 | 4.10 | Shot Peen + Cad Plate + Chromate |
| S53A-2 | 5-P | 6-P | 1.4.10 | 1.4.10 | Shot Peen + IVD-AJ Plate + Chromate |
| S53A-3 | (0-G) | (0-G) | 1.6 | 6 | Shot Peen + Passivate + Chromate |
| S53A-4 | (0-G) | (0-G) | 1.6 | 6 | Shot Peen + Passivate |
| S53A-5 | Removed 8/15/05 | | | | Grill Blast + Passivate + Chromate |
| S53A-6 | (0-G) | (0-G) | 1.6 | 6 | Grill Blast + Passivate |

*Per ASTM D-610-01
( ) Rating is the degree of red rust on the panel surface.

**Observation Comment List**

1. All four narrow sides appear similar to either the Skyward and/or Groundwater sides (faces).
2. No apparent visual change.
3. One blister under surface treatment.
4. Dark (black) pinpoint corrosion spots.
5. Light red rust on surface.
6. Dark red rust on surface.
7. One pinpoint red rust spot at a scratch on the panel surface.
8. All four narrow sides appear similar to the Skyward side (face).
9. All four narrow sides appear similar to the groundwater side (face).
10. White point corrosion product deposits on the surface.

Figure 8 shows the surfaces of 15-5 PH and S53 specimens after the 1-year beach exposure. The typical pit depth in S53 was 0.001-0.003 in, while the typical PH15-5 pit depth was 0.0005 in. (Note, however, that S53 is a 285 ksi steel, while 15-5 PH is only 195 ksi.)

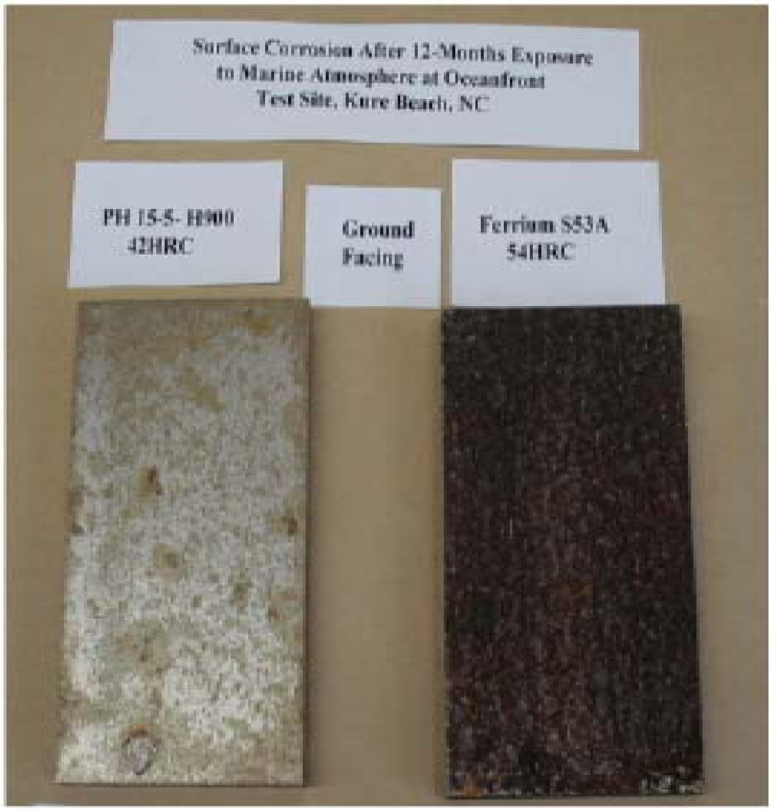



**Figure 8. Surfaces of Unpainted 15-5PH and S53 After 12-Month Beach Exposure—Kure Beach.**

### 4.1.9 Stress Corrosion Cracking

$K_{1SCC}$ is shown in Figure 9 as a function of applied potential (versus a saturated calomel electrode). The S53 performance was similar to PH15-5, far superior to 300M.

This means that an S53 component would be much less likely than a 300M component to fail by the unpredictable and often catastrophic SCC mechanism.

### 4.1.10 Hydrogen Embrittlement

Specimens of S53 plated with Cd, Ni, and Al all passed ASTM F519 testing.

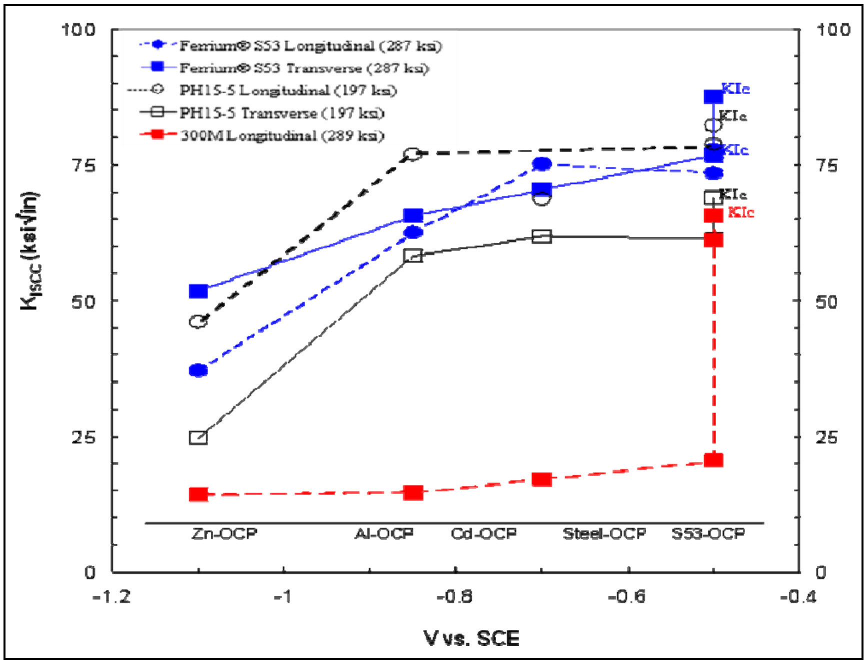



**Figure 9. SCC—Rising Step Load in 3.5% NaCl Solution per ASTM F1624-99.**

## 4.2 PERFORMANCE CRITERIA

The expected quantitative and qualitative performance and performance confirmation methods are shown in Tables 6 and 7.

**Table 6. Expected Performance and Performance Confirmation Methods—Quantitative.**

| Performance Criteria | Expected Performance Metric (Pre-Demo) | | Performance Confirmation Method | Actual Performance (Post-Demo) |
|---|---|---|---|---|
| **PRIMARY CRITERIA (Performance Objectives) (Quantitative)** | | | | |
| **Product testing** Corrosion testing, bonding capability, and metal fatigue testing | 1. UTS | 280 ksi minimum | ASTM E8 | 280 min |
| | 2. YS | 210 ksi minimum | ASTM E8 | 213 min |
| | 3. Elastic modulus | $29 \times 10^3$ ksi | ASTM E8 | $29 \times 10^3$ |
| | 4. El | >10% | ASTM E8 | 17 |
| | 5. RA | >48% | ASTM E8 | 56 |
| | 6. Fracture strength ($K_{1C}$) | >50 ksi√in | ASTM E399 | 62 |
| | 7. SCC fracture strength ($K_{1SCC}$) | >50 ksi√in | ASTM E399 | 77 |
| | 8. Corrosion resistance | Comparable with PH series stainless steels | ASTM B117 | Slightly lower, deeper pits |
| | 9. Fatigue | Fatigue life at least equivalent to Mil Handbook 5 (MIL-HDBK-5) 300M | ASTM E466 | √ |
| | 10. CVN impact energy | >20 ft/lb | ASTM E23 | 18 |
| **Hazardous materials** | Eliminate use of Cd-plated 300M landing gear components on initial set of problem components and finally across weapons systems overhauled at Ogden. Eliminates Cd and chromate conversion. | | Alloy chemistry and fly-to-buy ratio | √ for certain items |

**Table 6. Expected Performance and Performance Confirmation Methods—Quantitative** (continued).

| Performance Criteria | Expected Performance Metric (Pre-Demo) | Performance Confirmation Method | Actual Performance (Post-Demo) |
|---|---|---|---|
| **Factors affecting performance (pollution prevention)** | 1. Alloy production and heat treat—controlled by alloy production specifications and incoming inspection | ASTM E3 (metallography), ASTM D785 (hardness) | √ |
| | 2. Forging rate and method—controlled by forging specifications | ASTM E3 (metallography), ASTM D785 (hardness) | √ |
| | 3. Machining and grinding (grind burns)—controlled by machining specifications and inspections | Military Standard (MIL-STD)-867 | √ |
| | 4. Finished component heat treat—controlled by heat treating specifications | ASTM E3 (metallography), ASTM D785 (hardness) | √ |
| | 5. Passivation—controlled by passivation specifications | ASTM E3 (metallography) | √ |
| | 6. Shot peening (shot type and intensity)—controlled by shot peening specifications | MIL-S-13165A (shot peening) | √ |

**Table 7. Expected Performance and Performance Confirmation Methods–Qualitative.**

| Performance Criteria | Expected Performance Metric (Pre-Demo) | Performance Confirmation Method | Actual Performance (Post-Demo) |
|---|---|---|---|
| **PRIMARY CRITERIA (Performance Objectives) (Qualitative)** | | | |
| **Better durability of part/component** | Less corrosion, better damage tolerance | ASTM E399 | √ |
| **Less complex manufacturing** | No Cd plating and Cd chromating, no Cd stripping and Cd brush plate repair | Operating experience | √ |
| **Ease of use** | Manufactured and overhauled in essentially the same way as 300M components | JTP producibility tests; operating experience | √ |
| **SECONDARY PERFORMANCE CRITERIA (Qualitative)** | | | |
| **Reliability** | Reduced corrosion and SCC failures; reduced failures due to foreign object damage (FOD) | Operating experience | √ |
| **Safety** | No issues | | √ |
| **Versatility** | Same as 300M | Operating experience | √ |
| **Maintenance** | Less than 300M; no Cd stripping and plating | Operating experience | √ |
| **Scale-up constraints** | None anticipated | AIM tests | √ |

## 4.3 DATA EVALUATION

The only value in which S53 falls a little below the target is CVN energy. The alloy has nevertheless shown good fracture toughness, indicating ductile performance and strong resistance to crack propagation. S53 has been demonstrated to be as good as or better than 300M in impact energy testing.

Although S53 meets or exceeds almost all the objectives, cost analysis shows that it will not be used across all landing gear at Ogden because it will not be cost-effective to do so (see Section 5.0).

## 4.4 TECHNOLOGY COMPARISON

S53 is superior to 300M in all except tensile yield (213 min versus 230 min for 300M–see Table 4). Since the definition of tensile yield is essentially arbitrary (0.2% offset from the elastic curve), and Air Force landing gear are designed to ultimate, not yield, this is not considered to be a serious issue for Air Force landing gear. However, for other types of components, which are designed to yield, it could be a significant difference.

As expected, S53 is vastly superior to 300M in the area of corrosion resistance and corrosion-related properties such as corrosion fatigue and $K_{ISCC}$. In beach exposure and cabinet (B117) corrosion testing, S53 shows visual corrosion more rapidly than 15-5PH. After a year, the pit depth in S53 was up to six times deeper than in PH15-5, although the weight gain was only 50% higher, whereas the weight gain in 300M was an order of magnitude higher. This means that it S53 is close enough to 15-5PH in accelerated corrosion test performance that we will not be able to make a definitive statement about the relative service performance until there is enough experience to show how it actually performs in service.

The ultimate strength of S53 is, however, much higher than alternative CRES steels, such as 15-5PH, 17-4 PH, PH13-8Mo, and Custom 465. Thus, where an ultrahigh strength steel is needed, S53 offers significantly better corrosion performance than current high-strength steels and significantly higher strength than current CRES alloys.

# 5.0 COST ASSESSMENT

## 5.1 COST REPORTING

Cost analysis was carried out using the Calculation for Material Alternative Technologies (C-MAT)[3] method, with the cost evaluation being integrated into an Implementation Assessment[4], as we commonly do for these types of problems. The cost-benefit analysis was based on Hill AFB data for the period 2004-2005. The cost analysis was carried out for specific components that were identified by an evaluation of a large matrix of components overhauled at Ogden over this period. A limited number of components was chosen for detailed C-MAT analysis based on how well a simple spreadsheet analysis showed that they fit the profile of items likely to benefit from a CRES alloy and how well they illustrated the importance of different cost factors.

**Alloy cost:** The costs of alloys depend on factors such as heat raw material prices, some of which are quite volatile (e.g., Co), heat size (how many pounds in the heat), and form (ingot, bar, forging). Based on pricing at the beginning of the study, we have used the price of 300M as $3/lb and S53 as $15/lb. The S53 price has varied between $15/lb and $20/lb depending on time and lot size, while 300M has varied from $2.30/lb to $5/lb. S53 is similar in price to Aermet 100, which is used for most Navy landing gear.

Full data on overhaul and condemnation frequencies were not available to engineering. Therefore, approximations were made using data that could be interrogated.

- ❑ Cost of components, cost of repairs, and overheads came from the OO-ALC D035 database.
- ❑ Number of dispositions came from Air Force Materiel Command (AFMC) Form 202.
- ❑ Reason for condemnation for each condemned component was assessed from AFMC Form 202.

Form 202 was found to be a quite good method of determining the reasons for condemnation but is an underestimate of the total number of standard overhauls. This is because a Form 202 is primarily used to obtain engineering guidance on questionable components. Components that fall within the allowable limits of the Tech Order are usually repaired without a Form 202. It is also possible for components clearly worn or corroded beyond the limits specified in the Tech Order to be condemned without a Form 202 being issued, although this appears to be less common. Therefore, as S53 would be expected to reduce overhauls and condemnations, we should consider the cost analysis to be a conservative estimate of the cost-benefit of using S53.

---

[3] C-MAT, Calculation for Material Alternative Technologies, available from Rowan Technology Group (developed under SERDP funding).

[4] "Implementation Assessment - Replacement of Landing Gear Steel with S53 Corrosion-Resistant Steel", Keith Legg, Rowan Technology Group, December 2007.

Individual components have the following costs and savings associated with adopting S53:

Costs:

1. Higher component cost is due to the higher cost of the alloy because of its high Co and Ni content, higher machining costs, and higher heat treatment costs. (**This is usually the primary cost.)**
2. Qualification costs could include component and system level testing, up to the level of full landing gear rig tests and drop tests.
3. In most cases it will be necessary to replace not just items in service but also items in inventory, requiring additional purchases and carrying costs.

Savings:

1. Less time spent grinding out corrosion due to smaller pit depth (small saving)
2. Shallower corrosion pits, hence less material loss in grinding, hence more overhauls before condemnation, i.e., lower condemnation rate **(large saving for expensive parts)**
3. Lower occurrence rate, saving total maintenance, repair, and overhaul (MRO) cost for that part (moderate saving)
4. Less inventory needed (small saving)
5. Fewer service failures with all associated costs **(very large saving for some critical parts that may be associated with periodic landing gear service failures).**

To allow for inaccuracies in estimates, the cost model permits accuracies to be assigned to its inputs. The primary S-53 direct cost was that of the manufactured component. A material cost could be estimated quite accurately based on the forging weight and relative prices of S53 and 300M, while the cost of production was estimated based on a production model that incorporated the relative speed of machining from machining studies carried out in the program. The current component cost plus the cost differential due solely to material cost gives the minimum possible component cost.

## 5.2 COST ANALYSIS

Corrosion is the primary reason for condemnation of landing gear components (see Figure 7). In general, 300M is operated below the limits for failures, and even rather modest improvements should make a far more than proportional improvement in failure probabilities. At overhaul, corrosion and pit depths should be far less, usually avoiding the need for condemnation. Failures due to hydrogen embrittlement and SCC should be much less frequent, and only the harshest grind and arc burns should cause failure. We therefore chose to assume that the probabilities for condemnation of S53 components due to corrosion, SCC, hydrogen embrittlement, and arc and grind burns would be reduced to 20% of their current values. Condemnations for other causes remain unchanged. The result of this is summarized in Table 8. Clearly, these probabilities are unlikely to be accurate. These values were chosen for modeling purposes since there is no way to determine the actual values until a number of S53 items have been in service for several years.

**Table 8. Assumed Condemnation Probabilities for S53 Relative to 300M, with Consequent Condemnation Statistics.**

| Cause | # Condemnations | Percent | Probability with S53 | Expected Condemnations with S53 | Percent |
|---|---|---|---|---|---|
| Corrosion | 1,836 | 64.2% | 20% | 367 | 28.2% |
| SCC | 11 | 0.4% | 20% | 2 | 0.2% |
| Hydrogen embrittlement | 2 | 0.1% | 20% | 0 | 0.0% |
| Fatigue | 144 | 5.0% | 100% | 144 | 11.1% |
| Wear | 460 | 16.1% | 100% | 460 | 35.4% |
| Burn (arc or grind) | 97 | 3.4% | 20% | 19 | 1.5% |
| Overload | 123 | 4.3% | 100% | 123 | 9.5% |
| Bake | 52 | 1.8% | 100% | 52 | 4.0% |
| Other | 133 | 4.7% | 100% | 133 | 10.2% |
| **Total** | 2,858 | | | 1,301 | 45.5% |

Most calculations were made over the remaining life of the weapons system, rather than over the standard 15 years. The net present value (NPV) was plotted as a function of the number of years over which it is taken, with approximate $\pm 2\sigma$ lines (see Figure 7).

**Examples:**

**C-5 Roll Pin** (Figure 10)—This item has a major corrosion problem that has led to such frequent failures that replacements have not been able to keep up with condemnations (to such an extent that it was even cited in a Government Accounting Office [GAO] report). The cost analysis shows that the problem could be resolved through S53 substitution, resulting in an NPV of $6 million over the remaining life of the weapons system, with a 10-year payback period. This is an example of a high condemnation rate, part of which S53 is an ideal solution.

**B-1 MLG Cylinder** (Figure 11)—This item is expensive and has a high overhaul rate with a high condemnation rate for corrosion. By increasing the MRO cycle, the payback over the system life is about $20 million, with a 14-year payback period. This example shows the importance of considering inventory and MRO cycle changes.

| Value based on cost savings | | | | | |
|---|---|---|---|---|---|
| | | 5 year | 10 year | 15 year | 50 year |
| Net Present Value | | ($2,993,119) | ($719,238) | $1,053,320 | $6,588,493 |
| Internal rate of return | | | | | 2% |
| Return on investment | | -4% | 6% | 5% | 0% |
| Payback period | 7.4 | **10.5** | 16.1 | | |
| | min | **expected** | max | | |

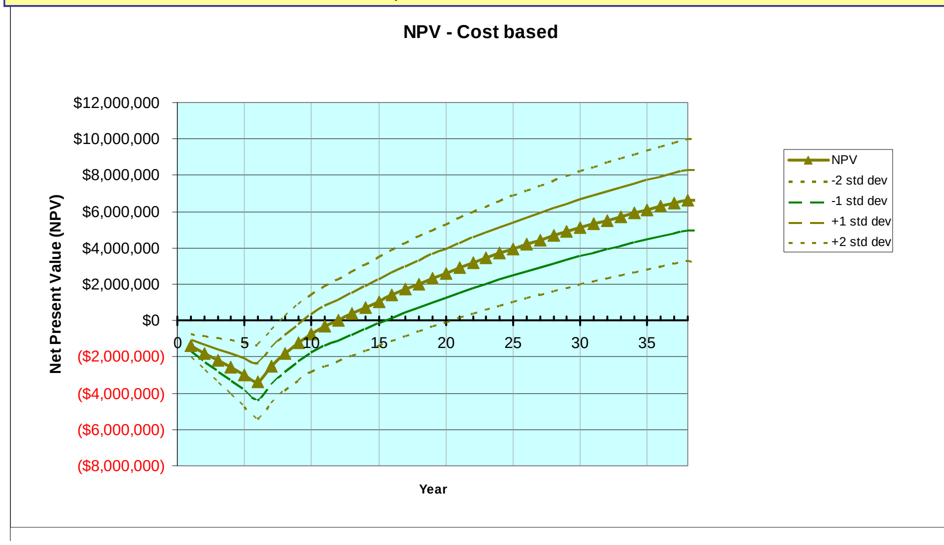



**Figure 10. NPV for C-5 Roll Pin Replacement with S53.** (Repair cost with S53 = 300M cost; S53 component cost = expected. Replace 300M components on overhaul. Inventory = 10% of items in service [as baseline]. Adoption cost = $1 million. Current cost = $15,278, S53; minimum cost = $24,613.)

| Value based on cost savings | | | | | |
|---|---|---|---|---|---|
| | | 5 year | 10 year | 15 year | 50 year |
| Net Present Value | | ($7,963,866) | ($8,854,100) | ($790,882) | $19,982,823 |
| Internal rate of return | | | | | 0% |
| Return on investment | | -5% | 6% | 6% | 0% |
| Payback period | 10.5 | **14.0** | 18.2 | | |
| | min | **expected** | max | | |

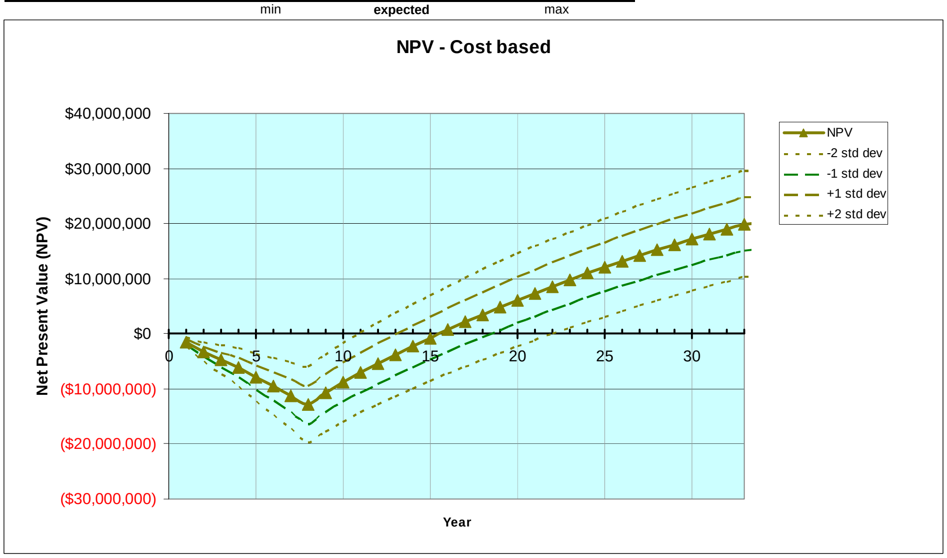



**Figure 11. Financial Performance Summary for B-1 MLG Cylinder Replacement with S53.** (Repair cost with S53 = 300M cost; S53 component cost = expected. 300M components replaced on condemnation. S53 MRO = 2x current. Current cost = $199,366; S53 minimum cost = $232,477.)

**A-10 MLG Piston** (Figure 12)—This component is currently made of 4330 steel, which has a lower tensile strength, making replacement with S53 a very low-risk proposition. Replacing it with S53 is not cost-effective when we consider only the overhaul and condemnation costs (top of figure). However, this component has suffered several mishaps in the past few years, with very high costs. The statistics are inadequate to determine a true service failure cost for the item, but for illustration, if we assume that the mishaps are corrosion-related and related to piston failures, then the cost-benefit changes dramatically (bottom of figure). Replacing the components greatly lowers the risk of failure, but that does not necessarily make it cost-effective to replace all the gear in the field. In fact, in this case a scenario in which this was done was not cost-effective.

## 5.3 COST COMPARISON

Clearly, S53 landing gear components are a cost-effective replacement for legacy components only for those situations where corrosion leads to high sustainment costs, such as:

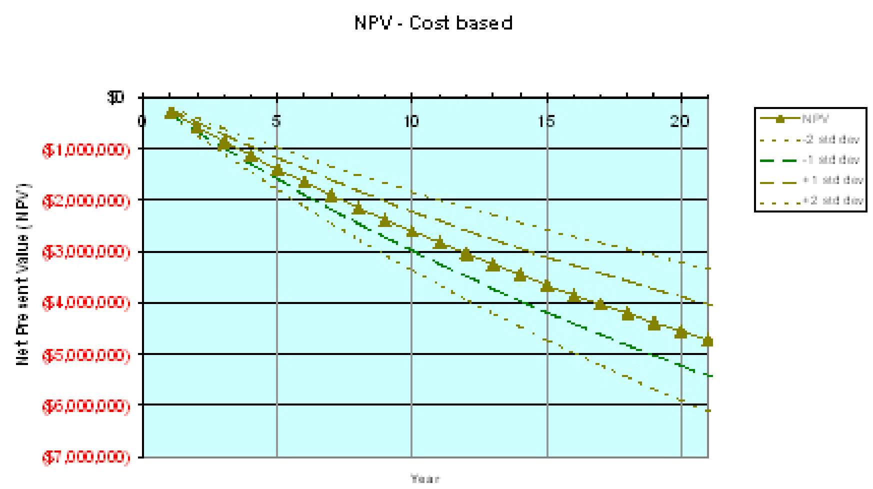
- ❑ Corrosion-related deterioration leads to a high rate of condemnation or high cost of overhaul.
- ❑ Corrosion-related deterioration leads to difficulty in maintaining readiness
- ❑ The legacy gear have a high risk of service failures leading to expensive or dangerous (Class A or B) mishaps. If these failures result from corrosion, SCC, or grind burns, then S53 is likely to greatly reduce their incidence; it will not affect the incidence of failures resulting from fatigue or overload except where it is used to replace lower tensile strength material.

The best replacement approach is to replace the specific components that tend to cause failures rather than to replace the entire gear, since this approach minimizes the cost. In doing so, however, it is important to avoid galvanic corrosion between components of different alloys.

Where components are creating an appreciable risk of failure, it will normally make sense either to replace them on overhaul or on an accelerated schedule, depending on the severity of the problem and availability of funds. The total cost of the accelerated approach is lower since it reduces service failure costs and may also reduce repair frequency or cost. It does, however, have a large up-front cost as the legacy components are replaced. One must remember when replacing fielded components that it is usually also necessary to replace the inventory to ensure that only the new items will be used in service.

**Value based on cost savings**

| | | 5 year | 10 year | 15 year | 50 year |
|---|---|---|---|---|---|
| Net Present Value | | ($1,402,801) | ($2,612,870) | ($3,656,686) | ($4,659,192 |
| Internal rate of return | | | | | |
| Return on investment | | | | | |
| Payback period | > 50 years | **>50 years** | > 50 years | | |
| | min | expected | max | | |




**Value based on cost savings**

| | | 5 year | 10 year | 15 year | 21 year |
|---|---|---|---|---|---|
| Net Present Value | | ($942,532) | ($1,088,182) | ($638,127) | $464,058 |
| Internal rate of return | | | | | |
| Return on investment | | -1% | 0% | 2% | 4% |
| Payback period | 0.0 | **17.1** | >50 years | | |

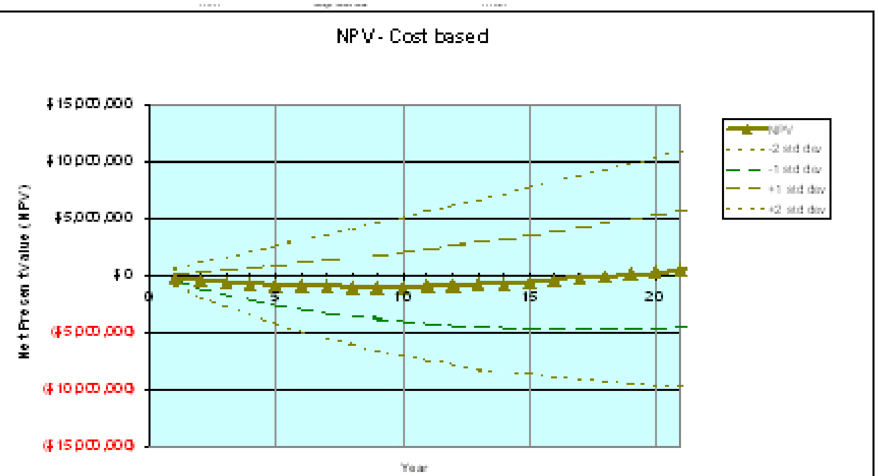



**Figure 12. Financial Performance Summary for A-10 MLG Piston Replacement with S53.**
(Top: Service failures excluded; repair cost with S53 = 300M cost;
S53 component cost = expected. 300M components replaced on overhaul.
Bottom: Same but service failure costs included.)

# 6.0 IMPLEMENTATION ISSUES

## 6.1 COST OBSERVATIONS

Materials cost is the primary factor in the cost difference between S53 and 300M ($15/lb versus $3/lb). S53 cost is relatively high and quite volatile because of its high alloy content (especially Co and Ni). S53, however, is not any more expensive than the Aermet 100 that is used to fabricate most Navy gear. At the same time, the price of all aerospace alloys has been high and deliveries have been very long over the past two or three years because of increased world demand.

The final cost of a component is the raw material cost plus the forging, heat treating, and fabrication costs. S53 components are somewhat more expensive to heat treat because the heat treatment is more complex and can be done only by a limited number of vendors who have cryogenic capabilities. In addition, the cost of fabrication is higher because some machining operations require slower speeds and feeds. However, it is likely that this will change as manufacturers gain experience with the material.

Table 9 shows the raw material and processing costs for 300M and S53, based on price quotes.

**Table 9. Raw Material and Processing Costs for Aerospace Grade 300M.**

| Material/Process | Price/lb 300M | Price/lb S53 |
|---|---:|---:|
| **Quote 1:** | | |
| 300M raw material (ingots) | $2.30 | |
| 300M bar stock (3.5-in diameter) | $5.10 | |
| 300M forged | $7.00 to $12.00 | |
| Hence, forging cost | $4.70-9.70 | |
| **Quote 2:** | | |
| 300M – 9-in round corner square billet<br>thermal condition: soft for cold sawing<br>Surface Condition: Fully Conditioned<br>Melt Type: Vacuum Arc Remelting (VAR) (remelt)<br>Specs: AMS 6257C, Test & Report AMS 2300K | | |
| Base price | $1.94 | |
| Raw material surcharge | $0.75 | |
| Transportation | $0.05 | |
| Total | $2.74 | |
| **Prices assumed for analysis:** | | |
| Raw material ingot | $2.75 | $15 |
| Forging | $7 | $7 |
| Bar production | $3 | $3-5 |
| Heat treating | $2 | $2.40 |
| Forging | $10/lb for 50 lb, falling to $4.50/lb for $1,600; max $7,500 | Same |

As a result of these various factors, the cost premium for an S53 part is lowest when the part is relatively complex so that machining is the major factor in the cost, and highest for a simple component that requires a heavy forging. Table 10 shows the costs for the components evaluated in this program. The minimum S53 component cost is simply the cost plus the material cost premium, while the probable cost takes into account the processing and fabrication. Note, for example, that the C-5 Bogie and the B-1 MLG cylinder have almost the same forging weight, and hence the same raw material cost. But the fabrication costs are very different. As a result, the percentage premium for S53 is far more for the cylinder, where the raw material is a larger factor.

**Table 10. Evaluated Components and Costs.**

| System | Component | Forging Weight | Cost 300M | Min Cost S53 | Probable Cost S53 |
|---|---|---|---|---|---|
| C-5 MLG | Roll pin | 571 | $15,278 | $24,613 | $27,349 |
| C-5 MLG | Bogie | 1,849 | $423,351 | $453,573 | $584,212 |
| B-1 MLG | Cylinder | 2,026 | $199,366 | $232,477 | $290,488 |
| A-10 MLG | Piston | 391 | $15,834 | $22,225 | $25,807 |
| F-16 HW MLG | Tension strut | 350 | $12,529 | $19,013 | $21,485 |

The cost-benefit is also strongly determined by the frequency with which components are condemned for corrosion-related causes, or worse, are the source of corrosion-related service failures such as SCC. Under these conditions, replacing condemned components with S53 can be very cost-effective. For components that are a source of service failures or failure risk, it may be worth replacing all the fielded components with S53, although this was not found to be cost-effective for any component that we evaluated.

## 6.2 PERFORMANCE OBSERVATIONS

***Performance advantages:*** S53 can in principle be used anywhere that 300M is currently specified. Its lower corrosion resistance makes it less prone to corrosion-related failure, such as:

- ❑ Corrosion
- ❑ SCC
- ❑ Corrosion fatigue.

In addition, the material appears to be more damage-tolerant than 300M and less sensitive to overheating and grind burning. It also appears to be less sensitive to hydrogen embrittlement. Together these features should reduce the probability of failure from the most common causes, including problems that sometimes arise during depot maintenance. Fatigue of S53 has been measured to be equivalent to or better than 300M. The wear properties of S53 have not been established, but, given its tensile strength and hardness, it is expected to be similar to 300M. By eliminating Cd plating, S53 also eliminates Cd embrittlement, which is a problem that sometimes occurs when an aircraft with Cd-plated gear is forced to abort a takeoff, causing very high heating of the landing gear and brake system, resulting in diffusion of Cd into the steel.

There do not appear to be any current uses of 300M for which S53 is technically unsuitable, although it will not always be cost-effective. For example, a test program is under way, funded by ESTCP, to evaluate S53 as an alternative for rotary gear actuators. Since this is an application where failure is primarily governed by galvanic corrosion, it is very different from S53 use in landing gear.

***S53 disadvantages:*** Although landing gear are designed to ultimate stress, some components are designed to yield stress. With its somewhat smaller Fty, S53 will not always work in those applications that are designed to yield.

S53 was designed to be used with protection provided by passivate, prime, and paint. However, because it does not appear to be quite as CRES as 15-5PH, it may require sacrificial corrosion protection for some applications. Although inferences may be drawn from cabinet corrosion and beach exposure tests, only service experience will reliably show if and where additional protection is needed. Where necessary, sacrificial corrosion protection can be supplied by ZnNi, Al, and other common coatings. (Recent experience, however, shows some indication that Al coatings may not be suitable because of their large galvanic potential difference.) The activation procedures for plating S53 are essentially those required for stainless steel and are therefore methods readily available at OEMs and depots.

There is one important difference that must be taken into account when an S53 component is used in an assembly with 300M or other non-CRES steels. The Open Circuit Potential of S53 lies in between stainless steels and high-strength steels. It may be important to protect the non-CRES components (especially Cd-plated components) from galvanic corrosion against the S53, which is normally done by applying a sacrificial coating. On the other hand, when used with stainless steel components (such as those made of 15-5PH), galvanic protection will not be needed as it is for 300M.

## 6.3 SCALE-UP ISSUES

Because the steel was designed by computational methods it does not have the kinetics problems that some other steels have had where the steel cannot be made over a certain size because it cannot be properly heat treated.

Therefore there appear to be no scale-up issues. Figure 13 is the Technology Readiness Level (TRL) matrix drawn from the Implementation Assessment. It shows that all data have reached a TRL of 5 (laboratory testing), while most of the manufacturing and producibility items are now at full production capability.

## 6.4 LESSONS LEARNED

In general there is no major difference in the use of S53 or 300M. The lower Fty for S53 could be an issue for some components. In general, however, the fact that S53 has higher Fty and Ftu than other CRES steels should make it a better material, capable of being a weight saving for components that are now made from lower strength CRES alloys such as 15-5PH, 17-4PH, and PH13-8Mo. As a result, although S53 was developed for landing gear, it may find initial applications in other components such as hydraulics and other actuators.

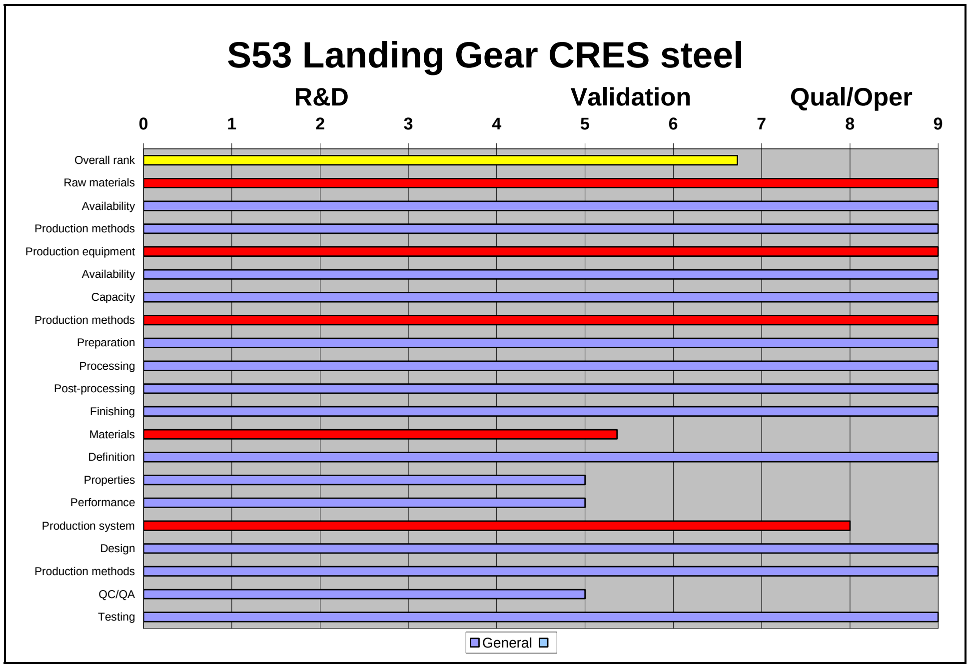



**Figure 13. S53 TRL Matrix.**

For potential users, the largest concern over the alloy has been its apparent more rapid corrosion in B117 and beach exposure tests. This is a purely visual assessment, and evaluation of pit depths shows that its actual corrosion rate is only slightly higher than other CRES alloys that have much lower strength. This is an issue that should be examined in more detail in order to fully understand exactly how it compares in service, since accelerated corrosion tests are notoriously unreliable.

## 6.5 END-USER/OEM ISSUES

End users were involved throughout the demonstration. Ryan Josephson of OO-ALC was the principal investigator and kept the landing gear group at Hill AFB apprised of progress. Heroux Devtek, the manufacturer of many of the replacement legacy landing gear purchased by Ogden, ran the machining studies and thus became familiar with using the alloy for manufacture. Cartech, the major U.S. specialty steelmaker, was the primary producer of material for this project and has become the first licensee for the alloy. Kropp Forge, who make the forgings A-10 landing gear, carried out the forgings for this program, with the buy-in from the program manager whose dies were used in the process.

The Air Force has funded a full-scale rig test of an A-10 landing gear fabricated from S53. This is a critical test required before A-10 gear can be flight tested. Because S53 has not been used previously on any other landing gear components it must successfully pass the A-10 SPO required tests and checks to ensure that it is flight worthy. S53 is a very low-risk replacement for this gear, which is made from lower strength 4330 steel.

A 12-month flight test is planned for one of the S53 A-10 cylinders manufactured during this program. The aircraft will proceed through its standard daily operations, and the S53 piston will go through periodic inspections for damage and corrosion throughout the 12-month evaluation

period. A successful evaluation will show that the S53 piston can perform without any problems or failures in its designed manner in a typical environment.

## 6.6 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

Before any alloy can be used for aerospace, it must have two critical items:

1. A commercial supplier
2. Industry specifications and engineering allowables.

S53 now has both of these.

- Cartech has licensed the S53 alloy from QuesTek. Cartech is the supplier for many aerospace alloys, including being the sole source for Aermet 100, which is used on most Navy aircraft. Latrobe Specialty Steel has also recently licensed the alloy. This means that the alloy will not be a sole source, which is important for most customers.
- AMS5922 was issued in January 2008 for procurement of S53 bar and forgings. This specification defines the composition, thermal processing, and inspection criteria to ensure that high quality production of S53 is maintained.
- An MMPDS listing is in the final stages of completion. A completed dataset for the MMPDS handbook has been submitted for analysis and will be presented to the MMPDS committee for review in April 2008, with publication to follow. The MMPDS listing establishes Class A allowables, which are the highest confidence allowables, required for most aerospace design.
- S53 has been issued an International Alloy Number, UNS S10500.

With these suppliers and specifications in place, S53 can now be used in aerospace component design. Both QuesTek and Ogden are moving ahead with plans to put S53 into production for new and legacy components. The A-10 rig testing is a critical part of Ogden’s efforts.

In addition to landing gear, an ESTCP program is in progress to evaluate the use of S53 for rotary gear actuators. In that program S53 actuators will be rig tested and, if successful and cost-effective, they may be flight tested on the F-35.

There are no regulatory compliance issues.

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# APPENDIX A

# POINTS OF CONTACT

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